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Conference Paper · July 2016

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AUTO-EXTINCTION OF ENGINEERED TIMBER: THE APPLICATION OF FIREPOINT THEORY

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ABSTRACT

Engineered timber products such as cross-laminated timber (CLT) are gaining popularity with designers due to attractive aesthetic, sustainability, and constructability credentials. The fire behaviour of such materials is a key factor preventing the widespread uptake of buildings formed predominantly of exposed, structural timber elements. Whilst guidance exists to determine the residual structural capacity of timber elements exposed to the 'standard fire', the predominant approach to solving the issue of increased fuel load is to fully encapsulate the timber elements, stifling architects' aspirations of exposed timber elements.

In this paper, the concept of auto-extinction – a phenomenon by which a timber sample will cease flaming when the net heat flux to the sample drops below a critical value – is explored experimentally and related to firepoint theory. A series of approximately 100 tests using the Fire Propagation Apparatus have been carried out to quantify the conditions under which flaming extinction occurs. Critical mass loss rate at extinction is shown to vary linearly with oxygen concentration from $3.5 g/m^2 s \pm 0.3 g/m^2 s$ at 21% oxygen to $4.1 g/m^2 s$ at 16%. External heat flux and airflow were not found to affect the critical mass loss rate within the ranges tested. Applying the firepoint equation to the experimentally obtained values demonstrates a good correlation to within $0.2 kW/m^2$. The analysis demonstrates that if the input parameters can be calculated sufficiently, then firepoint theory may be used to predict whether auto-extinction will occur. With further testing and refinement, this method may be applied in design, enabling architects' visions of exposed, structural timber to be realised.

INTRODUCTION & BACKGROUND

Cross-laminated timber (CLT) is one of several novel engineered timber products gaining popularity in the construction industry. This has been promoted by the drive towards improved aesthetic, structural, and sustainability credentials within the built environment. A significant factor preventing its widespread uptake in high-rise buildings is uncertainty as to its performance in the event of fire. The majority of existing research on timber's fire performance focuses on determining effective charring rates, with limited understanding of its behaviour in real (as opposed to standard) fire scenarios. As a result, current design guidance focuses on prescribing a fixed charring rate, with an additional "zero-strength" layer to account for the reduction in mechanical properties of the heated timber behind the char line[1]. In terms of accounting for the flammability of exposed timber, this is sometimes limited or prohibited by building codes, with arbitrary height limits set on timber construction in many jurisdictions[2]. As such, many CLT buildings to date have been fully encapsulated within gypsum plasterboard protection to satisfy such requirements, preventing full realisation of architects' aspirations.

In a building system with multiple exposed CLT surfaces, fire will result in ignition of the exposed timber. After burnout of the compartment fuel load, the radiative exchange between the exposed timber surfaces will drive the pyrolysis and hence continuation, or otherwise, of flaming. The mass flux of volatiles generated can be estimated through a heat transfer analysis and application of firepoint theory[3]. The mass flux of flammable pyrolysate can then be compared to critical mass fluxes determined experimentally to determine if auto-extinction of the exposed timber will occur. In order for architectural visions of exposed, structural CLT members to be achieved, its fire behaviour in such scenarios must be properly understood.

CRITICAL CONDITIONS FOR SUSTAINED FLAMING

Upon heating, timber pyrolyses, producing flammable and inert gases, tars, and a rigid, carbonaceous char layer[4]. Flaming ignition of the volatiles is possible only if a mixture of gases and air exists within the flammability limits and at the right temperature. Smouldering ignition of the char layer is also possible, but does not usually occur simultaneously with significant flaming combustion[4, 5]. As a result, under flaming conditions, the char layer will continue to increase in thickness[4], reducing the rate of heat transfer to the virgin timber and resulting in a subsequent gradual decline in pyrolysis rate and hence mass flux of pyrolysate[6, 7]. This condition is known as the firepoint[3].

Flaming extinction and piloted ignition have the same critical conditions[8, 9], with both being dependent on fire point conditions[10]. A flame will extinguish if the production of flammable vapours drops below a critical value, $\dot{m}''_{cr}$, due to the air:fuel ratio adjacent to the solid surface dropping below the lower flammability limit. The mass loss rate per unit area can be expressed in terms of the net heat flux by Equation 1[11]:

$$\dot{m}''_{cr}=\frac{\dot{Q}''_{net}}{L_v} \qquad [1]$$

where $\dot{m}''_{cr}$ is the mass loss rate per unit area, $\dot{Q}''_{net}$ is the net heat flux, and L_v is the heat of vaporisation. Since vaporisation will occur for the virgin wood rather than the char, it is the net heat flux at the interface between the timber and char that is of interest – a detailed understanding of heat transfer and surface losses is necessary to estimate this value.

AVAILABLE KNOWLEDGE

Firepoint theory

Rasbash et al.[3] present a method for quantifying the ignition and extinction conditions of a solid fuel in relation to the mass flow of volatiles released. This was accomplished by conducting a series of experiments on PMMA samples in the “firepoint apparatus” – a radiant panel heating a sample from above – to determine the effects of incident heat flux, air flow and oxygen concentration on the critical mass flux. Close to the critical heat flux for piloted ignition (12kW/m^2 to 19kW/m^2), the critical mass flux was found to increase with heat flux, from about 3.8g/m^{2}s to 5.2g/m^{2}s; thereafter it became independent of external heat flux. This initial variation was attributed to flame behaviour varying with heat flux. The effects of airflow were also explored; an initial drop from around 5.3g/m^{2}s to 3.2g/m^{2}s was observed over the range of 0 to 30lpm of airflow, before rising again to around 5.0g/m^{2}s at 60lpm. Reducing the oxygen concentration below ambient resulted in a sharp increase in critical mass flux from around 3.3g/m^{2}s to 10.4g/m^{2}s at 19% O_2.

Rasbash et al[3] concluded that that firepoint theory may be used to determine if a sample will continue burning in the absence of a supporting heat flux through Equation 2:

$$S = \phi \Delta H_{c,net}+L_v(\phi-1)\dot{m}''_{cr}+\dot{Q}''_e-\dot{Q}''_l \qquad [2]$$

where ϕ is the critical ratio of convective heat transfer to the heat of combustion of the volatiles, ΔH_c is the net heat of combustion of the solid, L_v is the heat of vaporisation, and $\dot{Q}''_e$ and $\dot{Q}''_l$ are the external heat flux and heat losses respectively. If $S>0$, the flame will be sustained, but if $S<0$, extinction will occur. Equation 2 is an expansion of Equation 1, with the net heat flux expanded into different components. This can be simplified into Equation 3:

$$\dot{m}''_{cr} = \frac{\dot{Q}''_e + \dot{Q}''_f - \dot{Q}''_l}{L_v} \qquad [3]$$

where $\dot{Q}''_f$ is the heat flux from the flames to the sample surface.

Tewarson and Pion[11] experimentally determined values for the heat of gasification, L_g, for various solids using differential scanning calorimetry (DSC). For timber, they found a heat of gasification of 1.82kJ/g. The heat of gasification includes the heat required to raise the solid to its pyrolysis temperature. Assuming a pyrolysis temperature of 300°C[6, 12] (noting that some pyrolysis will occur below this temperature, however the mass loss will be low and can be neglected[13]), the heat of vaporisation can be calculated from Equation 4[11]:

$$L_v = L_g - \int_{T_\infty}^{T_p} C_p dT \qquad [4]$$

where C_p is the specific heat capacity of the timber (using temperature dependent values from Eurocode 5[1]), and T_∞ and T_p are the ambient and pyrolysis temperatures respectively. This gives a heat of vaporisation of 1.1kJ/g.

Auto-extinction of timber

Limited data are available on the topic of flame extinction on timber surfaces. The earliest work was by Hottel[14], who subjected small-scale vertically orientated spruce samples to radiant heating and found that an incident heat flux of about 31.5kW/m^2 was required to sustain a flame for more than ten minutes.

Bamford et al.[15, 16] noted that for 230mm x 230mm wood panels with thicknesses varying from 9.5mm to 50.8mm heated by flames on two sides, after a given period of time, flaming will be self-sustaining upon removal of external heat sources. Panels heated only on one side, however, will not achieve self-sustained flaming if over 3mm thick. The time to reach sustained flaming was proportional to the square of sample thickness, with thicker samples taking longer. A minimum temperature of 200°C throughout the sample was required to sustain flaming. The conditions necessary for self-sustained flaming were found to relate to the rate of volatile production, with a critical rate of 2.5g/m^{2}s required for self-sustained burning.

Additional tests on 50mm thick oak and Columbian pine samples were carried out at heat fluxes ranging from 18 to 54kW/m^2. Samples subject to heat fluxes at or below 30kW/m^2 extinguished after reaching char depths of around 4 to 8mm, typically at times of around 2 to 7 minutes. The samples subjected to 50kW/m^2 however, continued burning until the majority of the sample had charred away. This critical heat flux of 30kW/m^2 is similar to that obtained by Hottel[14].

Further tests[16] explored the radiative feedback between two vertical wood panels set parallel and opposite each other. Square panels of length 229mm and rectangular panels 914mm x 381mm were set opposite each other and were ignited. The smaller, square panels were found to cease sustained flaming for separations above 51mm, and for the larger panels, around 127mm. This corresponds to view factors of 0.66 and 0.65 respectively, suggesting that in this setup these view factors correspond to the critical conditions for auto-extinction. The effect of airflow was also explored, and; as expected, a greater airflow resulted in longer times to ignition, but once ignited resulted in faster combustion due to improved mixing conditions.

Recent work in this area includes that of Inghelbrecht,[10] who tested 100mm x 100mm CLT radiata pine (ρ=635kg/m^3) samples of 72mm thickness and hoop pine (ρ=540kg/m^3) samples of 96mm thickness, Gympie messmate (an Australian hardwood) glulam samples (ρ=823kg/m^3) of 60mm thickness, and solid hoop pine (ρ=560kg/m^3) samples of 70mm thickness in the vertical orientation in a cone calorimeter. Samples were subjected to heat fluxes of 25, 40, 60, and 80kW/m^2 perpendicular to the grain for exposure times of 10, 20, 30, and 60 minutes. Temperatures were recorded using K-type thermocouples at depths of 5mm, 15mm, 25mm, 35mm, and 45mm from the heated surface. Mass loss was also recorded throughout the tests. For tests at 25kW/m^2, delamination occurred followed by flaming ignition. Upon removal of the external heat flux, the 80kW/m^2 samples (10 minutes exposure) extinguished after 2.5 minutes. The 25kW/m^2 samples (60 minutes exposure) experienced delayed self-extinguishment due to the delaminated first layer leaning against the rest of the sample and acting as additional fuel. The critical mass flux for flaming extinction in this setup was found to be around 4g/m^{2}s.

Crielaard[17] tested twelve 100mm x 100mm x 50mm thick softwood CLT samples under a cone calorimeter at 75kW/m^2. Temperatures were recorded by K-type thermocouples at various depths throughout the samples. Samples were moved to a second cone calorimeter, at a heat flux of 0 to 10kW/m^2, to determine the critical heat flux for smouldering extinction once the samples had reached char depths of 20mm. This critical heat flux was found to be around 5 to 6kW/m^2. The final two experiments had an additional airflow of 0.5m/s and 1.0m/s over the sample respectively. Whilst the 0.5m/s airflow led to quicker extinction than with no airflow, the 1.0m/s led to sustained burning at 6kW/m^2. Thus the natural convective airflow within a compartment may have a significant effect on smouldering extinction; this may also apply to flaming extinction, and is thus an important aspect to consider.

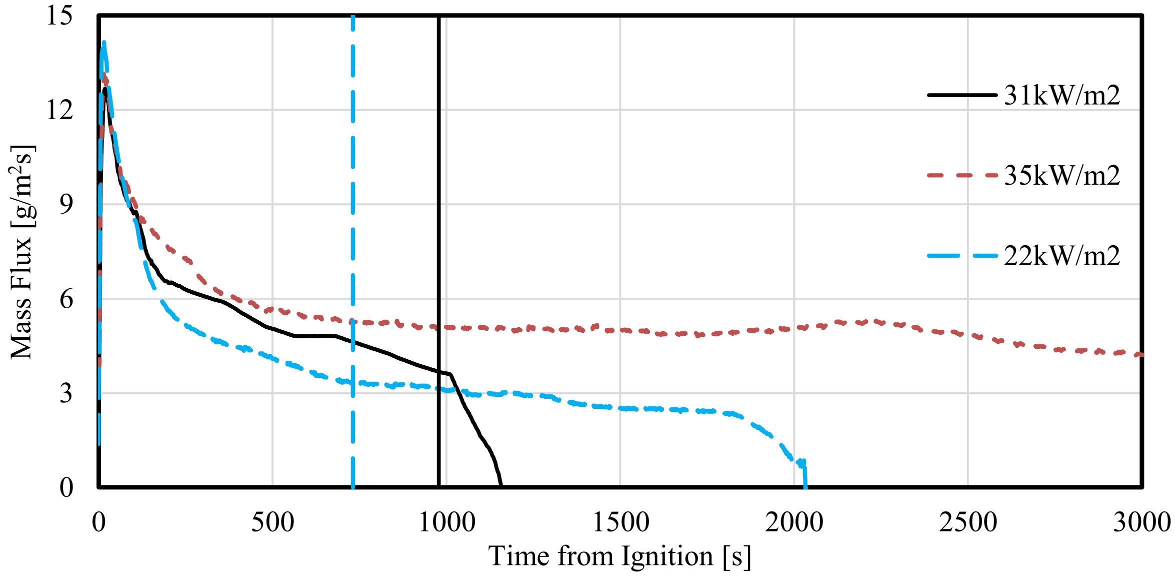
From the reviewed literature, it can be observed that flaming extinction is dependent on applied heat flux, oxygen concentration, and airflow conditions. However, this issue clearly requires further investigation to establish the conditions needed for auto-extinction if it is to be used, as has been proposed by the authors, as part of an engineering as a design method.

EXPERIMENTAL INVESTIGATIONS

A series of tests on 85mm x 85mm x 100mm thick softwood CLT samples of three uniform lamellae have been undertaken in the FM Global Fire Propagation Apparatus (FPA) to explore the conditions under which flaming extinction occurs. These consisted of constant heat flux tests, and two-phase tests in which the sample was exposed to a "high" heat flux for a prescribed time before reducing the heat flux to a "low" value to simulate the transition in heating from a fully developed compartment fire to heating from another burning CLT surface. Samples were wrapped (aside from the heat-exposed face) in aluminium foil and two layers of ceramic paper to promote one-dimensional heat transfer. Sample mass and dimensions were recorded before and after each test, and during the test oxygen calorimetry, and either mass loss or temperature measurements by K-type thermocouples inserted at depths of 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, 40mm, 50mm, and 60mm from the heated surface were taken.

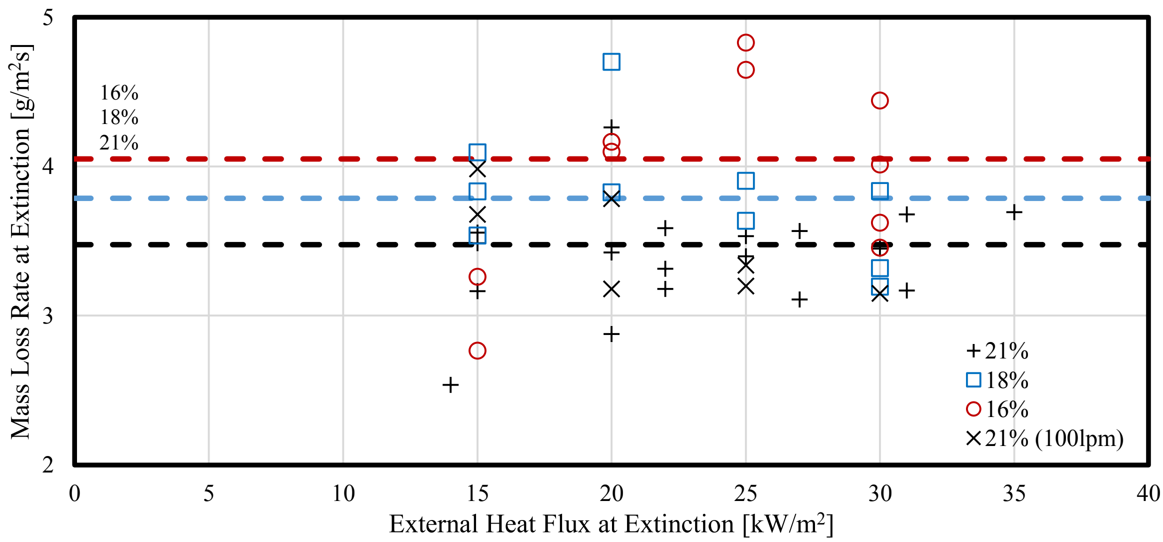
For constant heat flux tests, the applied heat flux was varied from 14kW/m^2 to 35kW/m^2. The critical heat flux for piloted ignition in this setup was found to be between 13kW/m^2 and 14kW/m^2. Tests at or below 31kW/m^2 were found to eventually undergo flaming extinction, whereas tests at or above 32kW/m^2 were found to undergo sustained flaming for an hour, at which point the test was terminated. Typical mass loss profiles are shown in Figure 1 for samples in which auto extinction, did or did not occur. In all cases the initial part of the mass loss rate (MLR) is dominated by a peak which subsequently decreases. The critical mass flux was found to be 3.48g/m^{2}s±0.3g/m^{2}s (based on the 25 and 75 percentile); this resulted in flaming extinction and was found to be independent of the external heat flux.

Figure 1: Mass loss rate as a function of time for samples at 22kW/m^2, 31kW/m^2, and 35kW/m^2, with flameout highlighted by vertical lines



The two-phase tests had an initial heating phase of a constant 40kW/m^2 incident heat flux for 30 minutes, before dropping to a constant heat flux of between 15kW/m^2 and 31kW/m^2. Most samples extinguished within two minutes after the drop in heat flux, with the notable exception being the samples for which the heat flux dropped to 31kW/m^2; two of which failed to extinguish and one of which only extinguished after an additional 37.5 minutes. This compares with approximately 17 minutes to extinguishing when exposed to a constant heat flux of 31kW/m^2. This again suggests a critical heat flux for extinction of around 31kW/m^2 in this setup, with the value being essentially independent of the pre-heating conditions. The mass loss rate at extinction was not affected. Tests in which temperature data were recorded showed similar times for flame out and found a critical temperature gradient at extinction of around 28K/mm at the char line.

Figure 2: Mass loss rate at extinction as a function of external heat flux and oxygen concentration



Tests were also performed at reduced oxygen contents of 18% and 16% to determine the effects of changes in the combustion environment, and hence the flammable mixture, on critical mass loss rates and critical temperature gradients. To reduce the oxygen concentration an inflow mix of a nitrogen/air at 100lpm was used. Comparative tests were also performed at ambient oxygen concentration with an inflow of 100lpm to determine the effects (if any) of increasing the airflow. The critical mass loss rate was found to increase to 3.8g/m^{2}s at 18% oxygen, and to 4.1g/m^{2}s at 16% oxygen. Increasing the airflow did not appear to have any effects on extinction criteria. Figure 2 shows mass loss rates at extinction as a function of external heat flux at extinction for each of the three oxygen concentrations tested. Apart from clear outliers, it is evident that mass loss is essentially independent of heat flux, as reported for PMMA samples tested by Rasbash et al.[3]

RELATION TO FIREPOINT THEORY

As previously discussed, Equation 3 (above) can be used to predict whether or not auto-extinction will occur. In this section an assessment is made of each of the three parameters to predict if auto-extinction occurs for a given scenario.

External Heat Flux

The first parameter in Equation 3 is the external heat flux, necessary to enable burning of a thermally thick wood sample[8]. This serves as the control variable in the experimental investigations herein. In the case of the FPA experiments, this heat flux is simply the incident heat flux from the lamps, which is a known value. The FPA comprises four tungsten filament lamps intended to give uniform irradiation over the surface of a sample[18]. It is similar to the cone calorimeter in size and test method, however the rapid thermal response of the lamps means that, unlike the cone calorimeter, tests can be run under controlled varying time-histories of heat flux. It is noteworthy that the FPA has its spectral energy emission peaks at 0.89 and 1.15 microns,[18] whereas flames from bio-based materials can have emission peaks as high as 4.5 microns[19]. The quartz around the heating elements in the FPA absorb any emissions above c.2 microns[18].

It has been found for timber char that the absorptivity, α varies as:

$$\alpha = 0.78 + \frac{0.18}{\lambda^{1/2}} \qquad [5]$$

where λ is the radiation wavelength in microns[20]. Thus for the FPA, α = 0.95 to 0.97, whereas for flames α = 0.87. Whilst this presents some difference in the heat absorbed by a sample, these differences are sufficiently small that they can be accounted for within the experimental variability. Whilst the absorption spectrum of timber may be different to that of char, the surface will have charred by the time extinction occurs, and thus it is the absorptivity of char that is of interest for the present study.

Heat Flux from Flames

The second parameter is the heat flux from the flames, which can be estimated using Equation 6 (from Rasbash et al.[3]):

$$\dot{Q}_f'' = \phi(\Delta H_{c,net} + L_v) \qquad [6]$$

where ΔH_c has been experimentally determined herein as around 16.8kJ/g, consistent with values quoted in the literature[8, 12]. ϕ is the proportion of energy from the flames transferred back to the surface and can be estimated through Equation 7[3]:

$$\dot{m}_{cr}'' = \frac{h_c}{C_{p,air}} \ln\left(1 + \frac{m_{og}}{r}\phi\right) \qquad [7]$$

where $C_{p,air}$ is the specific heat capacity of air, taken as 1.01kJ/kgK[21], m_{og} is the mass concentration of oxygen in air (0.23 at ambient oxygen concentration), r is the stoichiometric ratio of oxygen to fuel (taken as 3.43[3]) and h_c is the convective heat transfer coefficient, calculated by evaluating the Nusselt number over a horizontal plate using Equation 8[21]:

$$h_c = 0.54\sqrt[4]{\frac{g(T_s\text{-}T_\infty)}{LT_s v\alpha}}\, k \qquad [8]$$

where L is the surface length, T_s is the surface temperature, v is the kinematic viscosity of air, and α is the thermal diffusivity of air. The resulting convective heat transfer coefficient of around 9.3W/m^{2}K, thus $h_c/C_{p,air}$ = 9.2g/m^{2}s. Rasbash et al.[3] assume $h_c/C_{p,air}$ = 10g/m^{2}s for turbulent natural convection, similar to the value calculated herein. Substituting in the experimentally obtained values into Equation 7, gives ϕ = 0.15, and $\dot{Q}_f''$ = 2.6kW/m^2 for an ambient oxygen concentration, reducing to 2.1kW/m^2 and 1.7kW/m^2 for 18% and 16% oxygen concentrations respectively.

The mass flow of oxygen can be calculated from Equation 9[3]:

$$\dot{m}_{O_2}'' = \frac{h_c}{C_{p,air}}\ln(1\text{-}m_{og}) \qquad [9]$$

This gives values of 2.7g/m^{2}s, 2.3g/m^{2}s, and 2.0g/m^{2}s for 21%, 18%, and 16% oxygen respectively. The total mass flow at extinction in each case (air plus volatiles) is 15.1g/m^{2}s.

Heat losses

The total heat losses from an FPA sample are due to: radiative and convective losses to the surroundings, conductive losses into the sample, and the heat absorbed by the char layer. To calculate these parameters, an estimate of surface temperature is required. An initial estimate can be obtained based on thermocouple data at extinction.

Radiative heat losses can be calculated from surface temperatures through Equation 10:

$$\dot{Q}_{l,r}'' = F_{s,atm}\varepsilon\sigma(T_s^{\,4} - T_\infty^{\,4}) \qquad [10]$$

where $F_{s,atm}$ is the view factor from the sample to the surroundings (calculated to be around 0.85), ε is the surface emissivity, and σ is the Stefan-Boltzmann constant.

Convective heat losses can be calculated simply from Equation 11:

$$\dot{Q}_{l,c}'' = h_c(T_s - T_\infty) \qquad [11]$$

where h_c is as calculated previously.
Conductive heat losses can be calculated from Equation 12[10]:

$$\dot{Q}_{l,cond}'' = -k_{wood}\left.\frac{\partial T}{\partial x}\right|_{x=x_c} \qquad [12]$$

where k_{wood} is the thermal conductivity of the wood at the char line.

Finally, the heat absorbed by the char layer can be estimated from Equation 14:

$$\dot{Q}_{abs,char}'' = \int_0^{x_c}\frac{C_p m}{At}\,dT \qquad [13]$$

If char thickness is assumed constant over the time of interest, then this can be simplified to Equation 14:

$$\dot{Q}''_{abs,char} = \beta \int_{T_c}^{T_s} \rho C_p dT \quad [14]$$

where β is the experimentally-determined charring rate.

In summary, Equation 3 can be expanded into Equation 15, from which a theoretical critical mass loss rate can be calculated as:

$$\dot{m}''_{cr} = \frac{\dot{Q}''_e + \phi(\Delta H_{c,net} + L_v) - F_{s,atm}\varepsilon\sigma(T_s^4 - T_\infty^4) - h_c(T_s - T_\infty) + k_{wood}\left.\frac{\partial T}{\partial x}\right|_{x=x_c} - \beta \int_{T_c}^{T_s} \rho C_p dT}{L_v} \quad [15]$$

Solving Equation 2 for a 15kW/m^2 incident heat flux and assuming a surface temperature of 350°C from thermocouple data, gives S = 0.2kW/m^2 – implying sustained flaming, but close to the critical condition. Equation 15 gives a theoretical mass loss rate of 3.2g/m^{2}s, within 7% of the experimental value of 3.5g/m^{2}s. A sensitivity analysis revealed that the expression for radiative heat losses, in particular surface temperature, dominates. Varying the assumed surface temperature by ±50K results in a change in S of +2.6/-3. Thus obtaining accurate estimates for surface temperature is vital in predicting correct values.

RELATION TO COMPARTMENT FIRE

The firepoint principle can also be applied to a compartment fire scenario. Each of the parameters discussed for the lab-scale experiments can, in theory, be calculated for a compartment fire scenario to predict whether auto-extinction will occur after burnout of the initial fuel load.

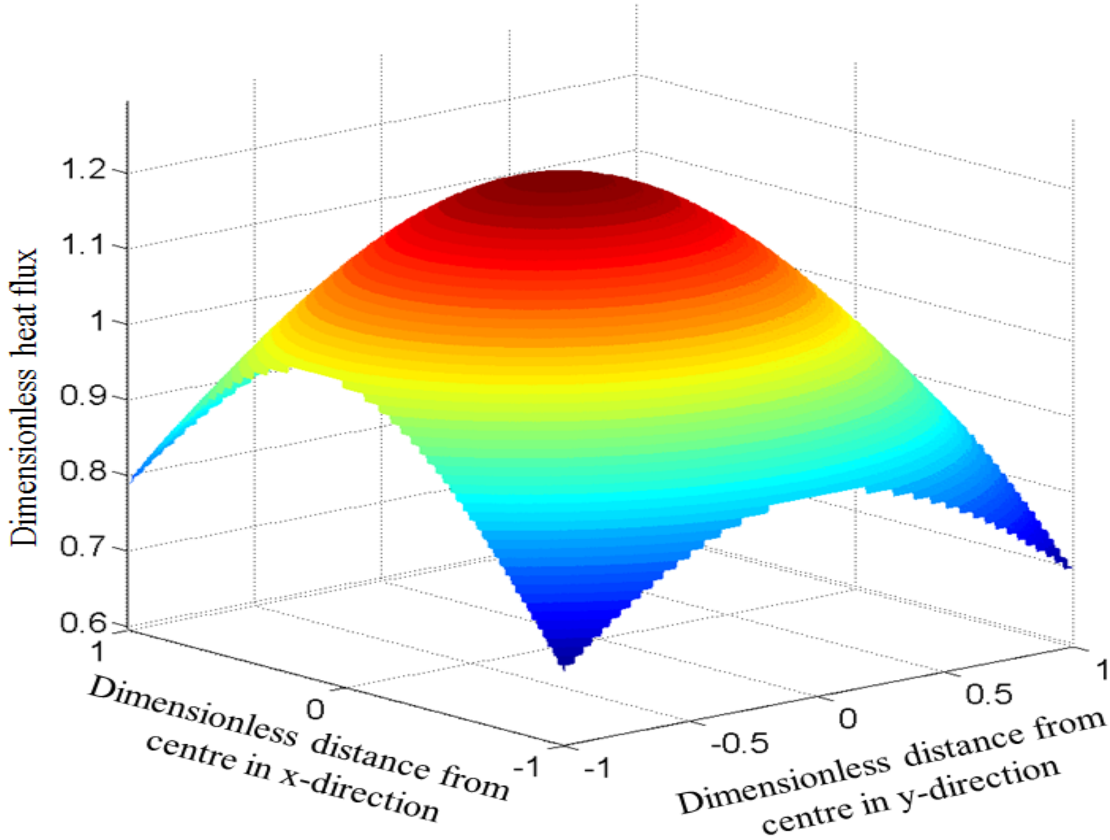
External Heat Flux

In a system with multiple exposed timber surfaces, the heat produced by each burning surface will radiate heat to all the other surfaces. If the characteristic wall temperature is known, then the incident heat flux can be calculated from configuration factors through Equation 16:

$$\dot{Q}''_f = F_{ij}\varepsilon\sigma T_c^4 \quad [16]$$

where F_{ij} is the configuration factor, ε is the surface emissivity, σ is the Stefan-Boltzmann constant, and T_c is the characteristic surface temperature, which is a weighted average of flame temperature and char temperature considering the prevalence of flames on the burning surface. As an example, the variation in dimensionless heat flux, $\dot{Q}''_f/\overline{\dot{Q}''_f}$, (where $\overline{\dot{Q}''_f}$ is the average heat flux over the surface) in the x- and y-directions is shown in Figure 3 for two equal area and opposite surfaces. These are calculated using configuration factor expressions from Howell[22]. The heat flux is largest at the centre of the surface, and thus extinction is theoretically likely to initially occur furthest away from the centre, with the central portion expected to be the last to extinguish. In practice, local effects may dominate.

Figure 3: Variation in dimensionless heat flux between two equal and opposite surfaces



Heat flux from flames

The heat flux from the flames can be calculated using Equation 5, as for the FPA.. In a compartment, experimentally, $\boldsymbol{h_c}$ is about 10 to 40W/m^{2}K[10], with an average value of 25W/m^{2}K usually taken during design – significantly higher than that in the FPA. Additionally, due to the elevated gas temperatures, the specific heat of air will be higher, rising almost linearly to 1.189kJ/kgK at 1300K[21]. This puts ϕ in the range of 0.13 to 0.62, corresponding to a heat flux from the flames of 6.7±4.4kW/m^2.

Heat Losses

Heat losses in a compartment fire setting will be significantly different to a lab-scale setup. In particular, the circulation of hot gases in a compartment, will mean that convective heat losses will be minimal.

Radiative heat losses to other non-timber surfaces may be significant, depending on the building materials used. As with the heat exchange between timber surfaces, this can be estimated based on configuration factors and surface temperatures however, high surface temperatures will result in a net reduction of heat losses by radiation.

As a result, the main source of heat losses will be conductive heat losses into the walls, which can again be calculated from Equation 12.

CONCLUSIONS AND FURTHER WORK

From the data presented in this paper, it can be reasonably hypothesised that if the heat flux to an exposed timber element within a fire compartment is such that the mass loss rate will be less than 3.5g/m^{2}s at ambient oxygen concentrations, and/or the temperature gradient at the char line is less than 28K/mm, then auto-extinction will occur. The critical mass loss rate was found to increase linearly with decreasing oxygen concentration up to 4.1g/m^{2}s at 16% oxygen, consistent with the findings of Rasbash et al.[3]. Airflow was found to have no clear effect on extinction conditions over the range tested. However, since airflow was identified by Rasbash et al.[3] as affecting extinction, a wider range of airflow rates, and their effects on extinction, should be investigated.

Firepoint theory has been successful in predicting critical mass loss rate at extinction for a case with a reasonably well-known surface temperature. Since the method is sensitive to surface temperature, accurate predictions of surface temperature are vital if the method is to be used in a predictive (or design) capacity.

Large-scale tests should be undertaken to verify (or otherwise) this approach at realistic scales. Additional factors which may affect extinction criteria such as smouldering or delamination[17], should also be explored and quantified to enable the use of auto-extinction as a design criterion.

ACKNOWLEDGEMENT

The authors gratefully acknowledge generous support from Ove Arup and Partners Ltd., partly through EPSRC iCASE Studentship 14220013.

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